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A Critical Assessment of Selected Past Research on Optical Turbulence Information in Diverse Microclimates

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A Critical Assessment of Selected Past Research on Optical Turbulence Information in Diverse Microclimates

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Abstract

Due to the increased use of laser and ground-to-satellite communications the need for reliable optical turbulence information is growing. Optical turbulence information is important because it describes an atmospheric effect that can degrade the performance of electromagnetic systems and sensors, e.g., free-space optical communications and infrared imaging. However, critical analysis of selected past research indicates that there are some areas (i.e., data and models) in which optical turbulence information is lacking. For example, line-of-sight, optical turbulence data coupled with atmospheric models in hilly terrain, coastal areas, and within built-up urban areas are few in number or non-existent. In addition, the bulk of existing atmospheric computer models that are being used to provide estimates of optical turbulence are basically one-dimensional in nature and assume uniform turbulence conditions over large areas. Therefore, current optical turbulence theory and models may be critically deficient and in error for inhomogeneous turbulence conditions, such as those that occur in urban environments or environments with changing topography and energy budgets.

This paper summarizes selected past research on optical turbulence and the refractive index structure parameter (C_n^2) in diverse microclimates in an effort to identify deficiencies in the optical turbulence information database and to recommend improvements. The database presented here contains optical turbulence (C_n^2) information at different wavelengths and for different microclimate environments, e.g., in rural, hilly, desert, mountain-valley, urban, coastal, ocean, and arctic. The database includes several examples of measured and modeled values of C_n^2 in the atmospheric surface and boundary layers.

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Tables

1. Introduction

The propagation of electromagnetic signals and images through the atmosphere is affected by turbulent fluctuations in the refractive index of air (Fried et al., 1967;Tatarski 1971). These fluctuations or discontinuities in air density cause optical turbulence variations in the speed at which electromagnetic waves propagate. Optical turbulence can bring about image distortion and signal loss due to the refraction effects beam broadening, wander, and scintillation (Fried et al., 1967; Chiba, 1971; Ishimaru, 1978; and Parry, 1981, Andreas, 1990). As a result, optical turbulence can significantly degrade the performance of electro-optical and infrared sensors, such as advanced forward-looking infrared (FLIR) imaging systems (Beland, 1993). Optical turbulence can also affect the accuracy required of laser geodetic systems, which are used to make electronic direction and distance measurements in construction, engineering, and surveying (e.g., Brunner and Angus-Leppan, 1984; Murray and Rindal, 1999; Weiss et al., 1999). With the increased use of free-space laser and ground-to-satellite optical communications systems the need for reliable optical turbulence information is growing.

While better understanding these effects are valuable both to the commercial and defense sectors, our Laboratory s interests, naturally, are focused on the U.S. Army s troops, who will make extensive use of electro-optical and infrared sensors in surveillance, detection, recognition, and identification of targets in the lower atmosphere (http://www.darpa.mil/fcs/index.html, 03/26/02). Improved physics-based theory and models for optical turbulence information will provide the soldier with enhanced knowledge on the performance of critical systems.

Realistic and accurate optical turbulence theory and models, however, do not exist for all microclimate environments. In urban environments, for example, atmospheric computer models and field observations have focused on the urban energy budget, surface temperatures, and wind fields (e.g., Voogt and Oke, 1997; Grimmond and Oke, 1999; Masson, 2000; and Voogt and Grimmond, 2000). Existing turbulence data over cities include measurements of the zero-wind displacement height, surface roughness, fetch, and friction velocity (Roth, 2000). In contrast, only a few authors have reported on measurements and calculations of atmospheric refractivity within the urban environment and, for example, its effect on radio signal propagation and microwave communications (e.g., Cole et al., 1978; and Medeiros Filho et al., 1988).

Several authors, however, have reported on the use of optical and microwave scintillometers[1] to retrieve surface, lower, and middle boundary layer wind speeds, sensible heat flux, and moisture flux data. Porch et al. (1988) and Poggio et al. (2000), for example, have described scintillometers-retrieved crosswind flow and turbulence information over complex terrain for studies in atmospheric transport and diffusion. De Bruin et al. (1995), Andreas et al. (1999), Chebouni et al. (2000), and Green et al. (2000) have used scintillometery methods as a practical means for determining the path-averaged surface energy budget over varying landscapes. These scintillometer-retrieved data were said to have great potential for validating (larger-scale) model

[1] Scintillometers are ground-based, remote-sensing instruments designed to measure optical turbulence intensity along a line-of-sight path established between a transmitter and a downrange receiver. Scintillometer operation is based on the principle that scintillations (i.e., light intensity variations) occur as fluctuations in air density create refraction effects in propagating electromagnetic waves (Clifford et al., 1974). The refractive index structure parameter, C_n^2, is related to the intensity of these refraction effects.

forecasts and/or satellite derived estimates of surface temperature, soil moisture, humidity, etc.

Nevertheless, no new theory or models have as yet been provided for estimating optical turbulence and the refractive index structure parameter (C_n^2) due to inhomogeneous terrain and meteorology. The bulk of existing computer models that provide estimates of optical turbulence have been primarily one-dimensional in nature and assume uniform turbulence conditions over large areas. Therefore, current optical turbulence theory and models may be critically deficient and in error for inhomogeneous turbulence conditions, such as those that occur in urban environments or environments with changing topography and energy budgets.

This report presents a database of optical turbulence information in diverse microclimates based on selected past research in an effort to identify deficiencies in the optical turbulence information database and to recommend improvements. The database contains information related to optical turbulence and the refractive index structure parameter (C_n^2) at different wavelengths and for different microclimate environments, e.g., in rural, agricultural, hilly, desert, mountain-valley, urban, coastal, and ocean, and arctic environments. The database includes several examples of measured and modeled C_n^2 data from the earth s surface extending upward though the lower atmosphere.

Most of the optical turbulence (C_n^2) information reported here were compiled using published articles or abstracts provided by The Applied Science & Technology Index and the Institute for Scientific Information (ISI) Web of Science — Citation Databases. The American Meteorological Society, SPIE The International Society for Optical Engineering, and the Defense Technical Information Center (DTIC) Scientific and Technical Information Network (STINET) also provided on-line indices that were useful. These electronic resources can be found at the following www addresses: Applied Science & Technology index (http://proquest.umi.com/pqdweb); ISI Web of Science -- Citation databases (http://webofscience.com/), SPIE (http://www.spie.org/), AMS (http://ams.allenpress.com); and DTIC (http://stinet.dtic.mil/).

2. Background

The refractive index structure parameter, C_n^2, is a measure of the intensity of optical turbulence. Values of C_n^2 in the atmospheric surface layer near the ground have been generally observed to range from about 10^{-12} to 10^{-16} $m^{-2/3}$ (Kallistratova and Timanovskiy, 1971; Darizhapov et al., 1988). High values of C_n^2, 10^{-12} $m^{-2/3}$ or greater usually indicate a highly turbulent atmosphere and the potential for considerable visual blurring (e.g., the wavy lines one might encounter looking out over a hot paved road). At lower values of C_n^2, 10^{-16} to 10^{-15} $m^{-2/3}$, atmospheric optical turbulence might be considered negligible over shorter (≤ 2 km) optical paths although there could be other image-degrading effects due to aerosols, precipitation, fog, or smoke.

Most expressions for the refractive index structure parameter have been developed and applied to flat, uniform terrain and oceans, for steady state and homogeneous meteorological (turbulence)

flat, uniform terrain and oceans, for steady state and homogeneous meteorological (turbulence) conditions. Based on the structure function formulations given by Tatarski (1971), a useful expression for C_n^2 can be written as,

$$C_n^2 = 2\, b_n \varepsilon^{-1/3} K_H \left(\frac{\partial n}{\partial z}\right)^2 , \qquad (1)$$

where

b_n is one of the Obukhov-Corrsin (Kolmogorov) constants (≈ 1.6) (Obukhov, 1949; Corrsin, 1951; Andreas, 1987a; Hill, 1989),

K_H is the exchange coefficient for turbulent heat diffusion, i.e., $K_H = \dfrac{u_* k z}{\phi_H}$,

k is Karman's constant (≈ 0.4),

z is height above ground level (a.g.l.),

u_* is friction velocity,

ϕ_H is the dimensionless surface layer temperature lapse rate (Monin-Obukhov, 1954),

ε is the turbulent kinetic energy dissipation rate, i.e., $\varepsilon = u_*^3\,(\phi_m - \zeta)/kz$,

ϕ_m is the dimensionless surface layer wind shear,

ζ is the surface layer turbulence scaling ratio, i.e., $\zeta = kz \dfrac{g}{\theta} \dfrac{\theta_*}{u_*^2}$ (Monin-Obukhov, 1954),

g is acceleration due to gravity,

θ_* is the potential temperature scaling constant, i.e., $\theta_* = \dfrac{kz}{\phi_H} \dfrac{\partial \theta}{\partial z}$.

θ is potential temperature, i.e., $\theta = T\left(\dfrac{P_o}{P}\right)^{\kappa}$ where $\kappa = 0.286$, (close to the surface $T \approx \theta$),

T is air temperature,

P_o is the air's reference level or surface pressure,

and

$\partial n / \partial z$ is the partial derivative of the index of refraction (n).

Equation (1) is assumed valid for $|\vec{r}|$ in the inertial sub-range, where $|\vec{r}|$ is a turbulent eddy length scale between the inner (viscous-dissipation) and outer (energy producing) turbulent scales (Tatarski, 1971; Ochs and Hill, 1985). Numerous atmospheric surface layer models of this type have been developed for estimating the refractive index structure parameter, C_n^2, especially for visible, near-infrared, and infrared wavelengths (e.g., Wesely and Alcarez, 1973; Davidson et al., 1981; Kunkel and Walters, 1983; Andreas, 1988; Miller and Ricklin, 1990; Rachele and Tunick,

1994; de Bruin et al., 1995; Thiermann et al., 1995; Tunick, 1998; and Frederickson et al., 2000).

The refractive index in air (n) can be expressed in terms of air density (i.e., pressure, temperature, and water vapor content). The following equations are expressions for the real index of refraction in air as reported by Andreas (1988), who references Owens (1967) [also see Ciddor (1996)], for visible and near-infrared regions. Andreas' formulations, which are expressed in terms of air temperature, T, and absolute humidity, Q, alternatively can be given in terms of the conserved variables potential temperature (θ) and specific humidity (q). Absolute humidity expressed as $Q=\frac{100.\ e}{R_v\ T}$ where $R_v=461.50\ J\ Kg^{-1}K^{-1}$ is the gas constant for water vapor and vapor pressure, as shown in Hess (1979), given as $e \approx 0.622Pq$, combine to yield the expression $Q=0.348\frac{Pq}{T}$.

Within visible and near-infrared regions from 0.36 to 3 μm (as indicated by the subscript v), the real index of refraction in air can be written as,

$$n_v=1+\left(M_1(\lambda)\frac{P}{T}+1.61\ (M_2(\lambda)-M_1(\lambda))\frac{Pq}{T}\right)x\,10^{-6}, \tag{2}$$

which basically incorporates the first order terms of the refractivity (dispersion) and density formulas for dry air, water vapor, and carbon dioxide (Owens, 1967) as a function of wavelength (λ), where

$$M_1(\lambda)=23.7134+\frac{6839.397}{130-\sigma^2}+\frac{45.473}{38.9-\sigma^2}, \tag{3}$$

and

$$M_2(\lambda)=64.8731+0.58058\sigma^2-0.007115\sigma^4+0.0008851\sigma^6, \tag{4}$$

where $\sigma=\lambda^{-1}$ (wavelength^{-1}). Assuming steady state, homogeneous conditions, and considering the pressure partial derivative (in the surface layer) to be negligible, then taking the partial derivative of Eq. (2) yields,

$$\frac{\partial n_v}{\partial z}=\left(-M_1(\lambda)\frac{P}{T^2}-1.61(M_2(\lambda)-M_1(\lambda))\frac{Pq}{T^2}\right)x\,10^{-6}\frac{\partial\theta}{\partial z} \tag{5}$$
$$+1.61(M_2(\lambda)-M_1(\lambda))\frac{P}{T}x\,10^{-6}\frac{\partial q}{\partial z}.$$

The potential temperature (θ) and moisture (q) partial derivatives $\partial\theta/\partial z$ and $\partial q/\partial z$, can be calculated from atmospheric data via traditional surface layer profile theory (Monin and Obukhov, 1954). Similar expressions for the partial derivative of the refractive index can be derived for infrared (7.8 to 19 μm), near-millimeter (0.3 to 3 mm) and microwave (radio) wavelengths (reference Andreas, 1988), as had been shown, for example, in the paper given by Tunick and Rachele (1991).

3. The Database

Optical scintillometers have provided line-of-site C_n^2 data in several diverse microclimates for comparison to surface layer atmospheric turbulence model results. Radar and radiosondes also have provided data that have permitted profile estimates of C_n^2 to be calculated from the earth s surface extending upward through the troposphere. In this section a database of selected optical turbulence information is presented in Tables 1-3. The database has been divided into 10 microclimate categories in the following manner:

1. Rural - agricultural, forests, rivers, and lakes
2. Rural - hilly terrain
3. Desert - arid basins
4. Desert - mountain-valley
5. Urban - pavement, cement, and roadways
6. Urban - city and residential buildings
7. Coastal areas
8. Ocean - Northern latitudes to include Arctic ice and snow
9. Ocean - Mid-latitudes
10. Ocean - Tropical

The database is separated into categories that are likely to contain one or more elements, which strongly influence atmospheric turbulence and refraction for that area, e.g., altitude, solar heating, precipitation, winds, terrain, landscape, surface roughness, buildings, trees, vegetation, soil moisture, evaporation, snow, ice, and sea-surface temperatures. (Peixoto and Oort, 1992).

Table 1 lists selected C_n^2 data retrieved primarily from surface layer (and low-to-middle boundary layer) line-of-site electro-optical sensors. In addition, optical turbulence data through the top of the boundary layer and extending into the free atmosphere derived from radiosondes, radar, aircraft-mounted turbulence sensors, as well as wind speed and turbulence data derived from optical remote sensor devices are included in this portion of the database. The locations where the data were collected are described in the first column of the table. Sensor wavelength, line-of-site distance (optical path), and sensor mounting height above ground level are given in the center column. Principal scientists, and their laboratory, university, and corporate affiliations are given in the last column.

Table 1. List of selected optical turbulence (C_n^2) data in diverse microclimates.

Microclimate category / subcategory	Data summary	Lead Scientists / Laboratory, Agency, and University Affiliations
Rural — Agricultural, forests, rivers, and lakes		
Flat, grass-covered fields, Tsimlyan experiment station, Russian steppes	C_n^2, visible and near-infrared, derived from surface layer temperature and wind speed gradient data	Kallistratova and Timanovskiy (1971) Inst. of Atmos. Physics, USSR
Mixed forested area and grass-covered fields, Northern IL	C_n^2, optical, 0.6328 µm, laser scintillometer, LOS 0.24- and 1.7 km @ approx. 15 m a.g.l.	Coulter and Wesely (1980) Argonne National Laboratory, IL
Boulder Atmospheric Observatory, Erie, CO	C_n^2, radio wave, FM-CW boundary layer profiles	Gossard et al. (1984), CIRES, Univ. of Colorado
Meadows, grass-covered fields, and wooded areas, The Netherlands	C_n^2, radio wave, derived from a 30GHz (1 cm) radio link, LOS 8.2 km @ 44-77 m a.g.l.	Herben and Kohsiek (1984), Eindhoven Univ. of Technology and KNMI, The Netherlands
Grass-covered fields, The Netherlands	C_n^2, infrared, 10.6 µm, CO2 laser beam scintillometer, LOS 5.9 km @ 40 m a.g.l.	Kohsiek (1985) KNMI, The Netherlands
Snow-covered fields, U.S. Army Camp Grayling, Michigan	C_n^2, visible and millimeter wave; derived from measured turbulence spectra and co-spectra data; C_n^2, optical scintillometer, 0.55 µm, LOS 300 m @ 2m a.g.l.	Andreas (1987b) U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH
Flat, grass-covered field, Table Mountain Mesa, Boulder, Co	C_n^2, near-infrared, 0.94 µm, large aperture scintillometer, LOS 606 m @ 1.45- and 3.95-m a.g.l.	Hill and Ochs (1992), NOAA, Wave Propagation Laboratory, Boulder, CO
Tilled, bare soil field, Northern Texas	C_n^2, optical scintillometer, 0.94 µm, LOS 450 m @ 2m a.g.l.	Tunick, et al. (1994) U.S. Army Research Laboratory, Adelphi, MD
Open valley and vineyard, Northern Spain	C_n^2, near-infrared, 0.94 µm, large aperture scintillometer, LOS 875 m @ 4.0 m a.g.l.	de Bruin et al. (1995) Wageningen Univ., The Netherlands
Grass-covered field, Paris, France	C_n^2, optical scintillometer, 0.9 µm, LOS 260 m @ 2 m a.g.l.; C_n^2, infrared, 10.6 µm coherent lidar, LOS 1690 m @ approx.10 m a.g.l.	Drobinski et al. (1999) Laboratoire de Meteorologie Dynamique, France
Mixed farmland and forested area, Central Europe	C_n^2, near-infrared, large aperture scintillometer, LOS 4.7 km, @ 45 m a.g.l.	Beyrich et al. (2000) German Weather Service, Germany

Table 1. List of selected optical turbulence (C_n^2) data in diverse microclimates.

Microclimate category / subcategory	Data summary	Lead Scientists / Laboratory, Agency, and University Affiliations
CASES-99 field site, grass-covered field, Central Kansas	C_n^2 optical scintillometer, 0.94 µm, LOS 112 m @ 2.46 m a.g.l.; C_n^2, optical, 0.94 µm, large aperture scintillometer, LOS 420 m, @ 3.4-5.2 m a.g.l.	Hartogensis and van de Wiel (2000a,b) Wageningen Univ., The Netherlands
CASES-99 field site, grass-covered fields and wooded areas, Central Kansas	C_n^2, microwave, 915 MHz turbulent eddy profiler; C_n^2, radio-wave, 2.7 GHz FM-CW boundary layer radar	Ince et al. (2000) Univ. of Massachusetts, Amherst
Rural – Hilly terrain		
ASCOT experimental area; Geysers geothermal region, CA; Brush Creek, CO	Crosswind and turbulence data, optical anemometer, LOS 480 m @ 30-50 m a.g.l.	Porch et al. (1988) Los Alamos National Laboratory, NM
European mountain — valley site, Switzerland	Crosswind data, 0.8-0.9 µm, large aperture scintillometers, LOS 0.9-2.7 km @ 60-600 m a.g.l.	Poggio et al. (2000) Paul Scherrer Institute, Switzerland
Open valley — irrigated vineyard, Southern Ranges, New Zealand	C_n^2, optical scintillometer, 0.94 µm; C_n^2, 1.1 cm (microwave) scintillometer, LOS approx. 1970 m @ 30.3 m a.g.l. (on average)	Green et al. (2000) The Horticultural Research Institue of New Zealand, Kerikeri, New Zealand
Desert — Arid basin		
Clay and sand soil, desert shrubs, White Sands Missile Range, NM	C_n^2, large aperture scintillometer, LOS 250 m @ 2-34 m a.g.l.	Kunkel et al. (1981) U.S. Army Atmospheric Sciences Laboratory, NM
Clay and sand soil, desert shrubs, Dugway Proving Ground, UT	C_n^2, optical scintillometer, 0.94 µm, LOS 195- and 674 m @ 2 m a.g.l.,; derived C_n^2, millimeter	Biltoft and Ewald (1988) U.S. Army Dugway Proving Ground, UT
Clay and sand soil, desert shrubs, Near Beer-Sheva and Sde-Boker, Israel	C_n^2, visible HeNe laser, 0.63 µm; C_n^2, infrared, CO2 laser, 10.6 µm, LOS 2.0-3.5 km, 4-25 m a.g.l.	Sadot and Kopeika (1992) Ben-Gurion Univ. of the Negev, Beer-Sheva, Israel
Sandy soils, desert shrubs, White Sands Missile Range,NM	C_n^2, optical scintillometer, 0.94 µm, LOS 1 km @ 1 m a.g.l.	Vaucher et al. (1992) Science and Technology Corp., NM
Clay and sand soil, desert shrubs, White Sands Missile Range, NM	C_n^2, optical scintillometer, 0.94 µm, LOS 1 km @ 8- and 32-m a.g.l.	Orgill et al. (1993) Science and Technology Corp., NM

Table 1. List of selected optical turbulence (C_n^2) data in diverse microclimates.

Microclimate category / subcategory	Data summary	Lead Scientists / Laboratory, Agency, and University Affiliations
Desert – Mountain-valley regions		
Between Salinas and North Oscura Peak, White Sands Missile Range, NM	C_n^2, ground based laser scintillometers, 0.987 µm LOS 51.4 km @ avg. 760 m a.g.l.; C_n^2 derived from aircraft-mounted temperature and wind sensors	Venet (1998); Hahn et al. (1999) Phillips Air Force Research Lab, NM
Sparse grasslands, desert shrubs, Sonora Desert, Northern Mexico	C_n^2, near-infrared, 0.94 µm, large aperture scintillometer, LOS approx. 1800-, 1000-, and 830 m @ approx. 3- to 10-m a.g.l. (on average)	Chehbouni et al. (2000), Centre d Etudes Spatiales de la Biosphere (CESBIO), Toulouse, France
Urban – Pavement, cement, roadways		
Above a cement terrace, Pune, India	C_n^2, optical, HeNe laser scintillometer, 0.6328 µm, LOS 30- and 60-m @ 1.1 m	Raj et al. (1993), Indian Institute of Tropical Meteorology, Pune, India
Above a paved road, Northern Europe	C_n^2, optical, laser scintillometer, 0.67 µm, LOS 80- and 100- m @ 1.0 m a.g.l.	Thiermann et al. (1995), Scintec Instruments for Atmospheric Research, Germany
Above airport runways (projected)	Crosswind data, Long-baseline optical anemometer and atmospheric turbulence sensor	Ting-I Wang and Crosby (1996) Scientific Technology Inc., MD
Urban — City and residential buildings		
Above and in between city buildings, Central London	C_n^2, millimeter (110GHz); C_n^2, microwave (36 GHz), derived from log-amplitude fluctuation data, LOS 4.1 km @ 50 m a.g.l., on average	Cole et al. (1978) University College London, England
Above and in between city buildings, Central London	C_n^2, microwave, derived from wet- and dry-bulb temperature and wind data	Medeiros Filho et al. (1988) University College London, England
Coastal Areas		
Over barrier islands and along coastline, Chatham, MA	C_n^2, aircraft-mounted microwave refractometer, boundary layer optical turbulence data	Morrissey et al. (1987) Air Force Geophysics Laboratory, Hanscom, AFB
Over the continental and coastal regions of the Asiatic Arctic, Siberia	Radio-wave refractive index gradient data derived from radiosonde water vapor and temperature profile data	Darizhapov et al. (1988) Academy of Sciences, USSR
Southern California coastal region, Point Magu, CA	Radio-wave refractive index profiles derived from (uv/visible) Lidar and radiosonde retrieved water vapor and temperature data	Blood et al. (1994), Space and Naval Warfare Systems Command (SPAWAR) Systems Center, San Diego, CA

Table 1. List of selected optical turbulence (C_n^2) data in diverse microclimates.

Microclimate category / subcategory	Data summary	Lead Scientists / Laboratory, Agency, and University Affiliations
Southern California coastal region, Point Magu, CA	Radio-wave refractive index profiles derived from Ground-Based High Resolution Interferometer Sounder- and radiosonde-retrieved water vapor and temperature data	Wash and Davidson (1994) Space and Naval Warfare Systems Command (SPAWAR) Systems Center, San Diego, CA
Buckland Park VHF radar facility, Southern Australia	C_n^2, radio wave, 54.1 MHz (VHF) Doppler radar and thermosonde data	Hocking and Mu, (1997), Univ. of Western Ontario, Canada; Univ. of Adelaide, Australia
Over flat pastures, Purerua Peninsula, New Zealand	C_n^2, large aperture scintillometer, near-infrared source (approx. 0.9μm), LOS 248 m @ 2m a.g.l.	Nieveen et al. (1998) Wageningen Agricultural Univ., The Netherlands
Ocean — Northern latitudes, Arctic, ice and snow		
Over drifting snow and ice, Beaufort Sea, Northwest Canadian Arctic	C_n^2 data (climatology) derived from measured surface layer flux data	Andreas (1989), U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH
SHEBA Experimental site, Beaufort Sea, Northwest Canadian Arctic	C_n^2, optical scintillometer, 0.685 μm, LOS 300-350m @ 2.6 - 2.9 m a.g.l.	Andreas et al. (1999) U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH
Ocean — Mid-latitudes		
The Meetpost Noordwijk platform, North Sea	C_n^2, infrared, 3-5μm, LOS 18 km; Source @ 1.5 — 7 m above sea level; Receiver @ 15 m and 40 m a.g.l.	Schwering and Kunz (1995) TNO Physics and Electronics Laboratory The Hague, The Netherlands
EOPACE Experimental site, Point Loma, San Diego Bay, CA	C_n^2, mid-IR scintillometer, 3.8 μm, LOS 7 km, 4.9-6.2 m above sea level.	Frederickson et al. (1998, 2000) Naval Postgraduate School, Monterey, CA
Ocean — Tropical		
East of Singapore, close to the equator, South China Sea	Radio-wave refractive index gradient data derived from radiosonde water vapor and temperature profile data	Ong and Ong (2000) Nanyang Technical Univ., Republic of Singapore

Twenty-eight of the 52 citations given in Table 1 reference C_n^2 data at visible or near-infrared wavelengths, which include 4 reports of modeled C_n^2 data from meteorological gradients, i.e., Kallistratova and Timanovsky (1971), Andreas (1989), Venet (1998) and Hahn et al. (1999), 1 report of modeled C_n^2 data from measured turbulence spectra and co-spectra, i.e., Andreas (1987b), and 3 reports related to crosswinds and turbulence data collected from optical (anemometer) sensors. There were 6 reports of C_n^2 data at infrared wavelengths, which includes one report on estimates of C_n^2 derived from lidars, i.e., Drobinski et al. (1999). There was 1 report of modeled C_n^2 data for near-millimeter wavelengths, i.e., Andreas (1989), and 16 reports of C_n^2 data at radio (microwave) wavelengths, to include 1 reports on modeled estimates of C_n^2

from surface flux data (i.e., Biltoft and Ewald, 1988) and 4 reports on calculations of the radio refractive index gradient from radiosonde or remotely sensed water vapor and temperature data (i.e., Darizhapov et al., 1988; Blood et al., 1994; Wash and Davidson, 1994; and Ong and Ong, 2000). The paper by Darizhapov et al. (1988) provided information on refractive index profile structure through the lower troposphere over continental and coastal regions of the Asiatic Arctic, while Ong and Ong (2000) provided information on refractive index profile structure through the first kilometer over the South China Sea, close to the equator.

Citations for optical turbulence data at visible or near-infrared wavelengths were reported in each microclimate category, with the exception of ocean — tropical environments. Most of these citations referenced optical (~ 0.94 m) scinitillometer data that have been collected over various surfaces. They also included shorter wavelength (~ 0.63 m) laser scinitillometer data (e.g., Coulter and Wesely, 1980; Sadot and Kopeika, 1992; Raj et al., 1993; and Theirmann et al., 1995), as well as reports on laser infrared data at ~ 3-5 m and 10.6 m (e.g., Kohsiek, 1985; Sadot and Kopeika, 1992; Schwering ad Kunz, 1995; and Frederickson et al., 1998, 2000) which had been collected over forests and grass-covered fields, desert shrubs, sandy and clay soils, cement building terraces, roadways, and coastal seas. There were no reports, however, provided for visible or infrared C_n^2 data within cities.

Several reports were shown for boundary layer and tropospheric microwave C_n^2 data derived from radars, e.g., Gossard et al. (1984), Hocking and Mu (1997), and Ince et al. (2000), as well as reports already mentioned on optical turbulence information related to radio links and radio signal propagation closer to the ground over the urban landscape, e.g., Cole et al. (1978), Herben and Kohsiek (1984), and Medeiros Filho et al. (1988). Also, there were 2 reports given on measurements of low-to-middle boundary layer microwave refractivity and atmospheric effects on radio-wave propagation in coastal regions given by Blood et al. (1994) and Wash and Davidson (1994).

In contrast, Andreas (1987b) reported on estimates of C_n^2 for visible and millimeter (radio) wavelengths derived from micrometeorological turbulence spectra and co-spectra data collected through the surface layer over flat, snow and ice covered ground. Also, Green et al. (2000) reported on C_n^2 data retrieved from microwave (~ 1.1 cm) scintillometers aligned (at approx. 30 m a.g.l.) over an open valley and irrigated vineyard. Finally, modeled optical turbulence data derived from measured surface layer heat and moisture flux data (see Wesely, 1976) were reported by Biltoft and Ewald (1988) for dry desert vegetation with sand and clay soils, and by Andreas (1989) and Andreas et al. (1999) for estimates of C_n^2 over arctic snow and sea ice.

Table 2 lists selected computer models for estimating C_n^2 information within the atmospheric surface layer for various microclimate environments. These algorithms have been developed primarily for flat, homogenous areas, e.g., fields and farmlands, desert mesas, coastal waterways, and frozen arctic seas, to estimate values of C_n^2 mainly for visible, near-infrared, and infrared wavelengths. Such models have relied on traditional surface layer theory (Monin-and Obukhov, 1954) to produce first-order temperature, wind speed, and humidity gradient and profile structure information. From these meteorological data, values of C_n^2 were derived based on the structure function formulations given by Tatarski (1971). Numerous models of this type have been developed and implemented, as mentioned in Sect. 2 (Background) of this paper. One exception,

however, was the C_n^2 model based on the regression analysis of laser-retrieved angle-of-arrival and amplitude fluctuation data against standard meteorological observations in a desert environment (Sadot and Kopeika, 1992). Other exceptions include calculations for C_n^2 at visible and millimeter wavelengths from micrometeorological turbulence spectra and co-spectra data collected over snow and ice, and from atop an 11- story (~ 50 m a.g.l.) city building as described by Andreas (1987b) and Medeiros Filho et al. (1988), respectively.

In summary, 11 of these 22 citations shown in Table 2 have described model estimates that provide C_n^2 information for visible or near-infrared wavelengths, 6 for infrared wavelengths, 1 for near-millimeter wavelengths, and 4 for radio wavelengths. There were no citations here reported for optical turbulence (C_n^2) models in rural — hilly areas or desert — mountain-valley regions. There were no citations reported here for calculations of visible or infrared C_n^2 in built-up urban or industrial areas.

Table 2. List of selected computer models used in determining atmospheric surface layer optical turbulence (C_n^2) information.

Microclimate category / subcategory	Model summary	Lead Scientists / Laboratory, Agency, and University Affiliations
Rural — Agricultural, forests, rivers, and lakes		
Flat ground, grass-covered fields, steppes	C_n^2 visible and near infrared; Derived for daytime, nighttime, and transition periods using surface layer temperature and wind speed gradient data	Kallistratova and Timanovskiy (1971) Inst. of Atmos. Physics, USSR
Flat ground, vegetation or barren, damp or dry soil, snow and ice	C_n^2 visible; Derived for the diurnal cycle and varying conditions of atmospheric stability; Includes Monin-Obukhov (1954) turbulence scaling.	Wesely and Alcarez (1973) U.S. Army Ballistic research Laboratory, Aberdeen Proving Ground, MD
Flat ground, vegetation or barren, damp or dry soil	C_n^2 visible, near-infrared, and infrared; Derived from a model of the surface layer radiation and energy budget; Includes Monin-Obukhov (1954) turbulence scaling.	Rachele and Tunick (1994) U.S. Army Research Laboratory, Adelphi, MD
Vineyards and farmland	C_n^2 visible and near-infrared; Derived from temperature, moisture, and wind speed profile structure; Includes zero-plane displacement; Includes Monin-Obukhov (1954) turbulence scaling.	de Bruin et al. (1995) Wageningen Univ., The Netherlands
Flat ground, vegetation or barren, damp or dry soil	C_n^2 visible, near-infrared, and infrared; Derived from two levels of conventional surface layer temperature, moisture, and wind speed profile data; Includes Monin-Obukhov (1954) turbulence scaling.	Tunick (1998) U.S. Army Research Laboratory, Adelphi, MD
Rural – Hilly terrain		

Table 2. List of selected computer models used in determining atmospheric surface layer optical turbulence (C_n^2) information.

Microclimate category / subcategory	Model summary	Lead Scientists / Laboratory, Agency, and University Affiliations
Desert — Arid basin		
Clay and sand soil, desert shrubs	C_n^2 visible and near-infrared; Derived from energy balance relationships for the diurnal cycle and varying conditions of atmospheric stability; Includes Monin-Obukhov (1954) turbulence scaling.	Kunkel and Walters (1983) U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM
Clay and sand soil, desert shrubs	C_n^2 visible and millimeter wavelengths; Derived from expressions for the temperature and moisture structure parameters (Wesley, 1976).	Biltoft and Ewald (1988) U.S. Army Dugway Proving Ground, UT
Clay and sand soil, desert shrubs	C_n^2 visible and infrared; Derived using regression model for laser beam angle of arrival and amplitude fluctuation data and routine meteorological parameters.	Sadot and Kopeika (1992) Ben-Gurion Univ. of the Negev, Beer-Sheva, Israel
Desert – Mountain-valley regions		
Urban – Pavement, cement, roadways		
Above paved roadways	C_n^2 visible and near-infrared; Derived from temperature, moisture, and wind speed profile structure; Includes Monin-Obukhov (1954) turbulence scaling.	Thiermann et al. (1995) Scintec Instruments for Atmospheric Research, Germany
Urban — City and residential buildings		
Above multi-story buildings	C_n^2 microwave; Derived using a turbulence spectra model; Vapor pressure is determined from measured 1-Hz wet- and dry-bulb temperature data.	Medeiros Filho et al. (1988) University College London, England
Coastal Areas		
Ocean — Northern latitudes, Arctic, ice and snow		
Over the North Sea	C_n^2 infrared; Derived from marine layer surface stress and turbulence model formulations; Includes Monin-Obukhov (1954) turbulence scaling; Over-water fluxes of sensible heat and water vapor are calculated.	Schwering and Kunz (1995) TNO Physics and Electronics Laboratory, The Hague, The Netherlands
Over arctic ice and snow	C_n^2 visible, near-infrared, infrared, near-millimeter, and radio-wave; Derived from measured and modeled meteorological data; Fluxes of sensible heat and water vapor are calculated over snow and ice covered ground; Includes Monin-Obukhov (1954) turbulence scaling.	Andreas (1988) U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH

Table 2. List of selected computer models used in determining atmospheric surface layer optical turbulence (C_n^2) information.

Microclimate category / subcategory	Model summary	Lead Scientists / Laboratory, Agency, and University Affiliations
Ocean — Mid-latitudes		
The marine surface layer, coastal CA	C_n^2 visible; Derived for stable-inversion and unstable- convective conditions using standard meteorological inputs to determine air sea temperature, moisture, and wind speed differences; Over-water fluxes of sensible heat and water vapor are calculated; Includes Monin-Obukhov (1954) turbulence scaling.	Davidson et al. (1980, 1981) Naval Postgraduate School, Monterey, CA
The marine surface layer, coastal CA	C_n^2 infrared; Derived for stable-inversion and unstable- convective conditions using standard meteorological inputs to determine air sea temperature, moisture, and wind speed differences; Over-water fluxes of sensible heat and water vapor are calculated; Includes Monin-Obukhov (1954) turbulence scaling.	Frederickson et al. (1998, 2000) Naval Postgraduate School, Monterey, CA
Ocean — Tropical		

Table 3 lists selected computer models used in determining values for C_n^2 and atmospheric refractivity extending from the earth s surface upward though the troposphere. The right hand and center columns of Table 3 provide model summary information. Reference information, lead scientists, and labor ory, university, or corporate affiliations are given in the last column. Several of the citations reported here describe calculations of profile C_n^2 information up to 25 km for visible (optical) and microwave (radio) wavelengths determined via radiosonde or radar-retrieved temperature, humidity, and wind speed data (e.g., VanZandt et al., 1978; Gossard et al., 1982; d Auria et al., 1993; Dewan et al., 1993; and Walters, 1995). Several others, in contrast, report on atmospheric models of varying complexity that have been used to empirically derive or forecast this kind of upper-air optical and microwave C_n^2 profile information (e.g., Brookner, 1971; Hufnagel, 1974; and Good et al., 1988). Table 3 also references a calculation of microwave C_n^2 for the daytime convective case using higher order turbulence closure models of the atmospheric boundary layer (Burk, 1980; Gilbert et al., 1999). In addition, there are several reports on mesoscale numerical models that have been adapted for use in predicting the time-variant fields of optical and microwave refractivity over oceans (e.g., Burk and Thompson, 1997; Ruggiero and DeBenedictis, 2000; and Atkinson et al., 2001). It is seen that most profile and forecast models for estimating atmospheric refractivity have been developed for coastal and ocean regions. In summary, 7 of the 16 citations in Table 3 refer to models that have provided C_n^2 information for visible or near infrared wavelengths, 1 for infrared wavelengths, and 8 for microwave (radio) wavelengths. There were no profile or forecast model calculations reported here for near-millimeter wavelengths.

Table 3. List of selected computer models used to determine optical turbulence (refractivity) and C_n^2 profile information.

Range	Model summary	Lead Scientists / Laboratory, Agency, or University
0.1 km < h < 10 km a.g.l.	C_n^2 visible; Exponential decay model for C_n^2 for undisturbed daytime and clear sky nighttime conditions.	Brookner (1971) Raytheon Company, Wayland, MA
3 km < h < 24 km a.g.l.	C_n^2 visible; Empirical model derived from statistical analysis of stellar scintillation and tropospheric wind speed data.	Hufnagel (1974) The Perkin-Elmer Corp., Norwalk, CT
5 km < h < 15 km a.g.l.	C_n^2 microwave; Radiosonde temperature, humidity, and wind speed data model; Includes formulations of Tatarski (1971) for the radio refractive index structure constant.	VanZandt et al. (1978) NOAA Aeronomy Laboratory, Boulder, CO
10 m < h < 2000 m a.g.l.	C_n^2 optical and microwave; Higher-order turbulence closure model; Includes expressions for the temperature, and moisture structure parameters given by Wesley (1976).	Burk (1980) Naval Environmental Prediction Research Facility, Monterey, CA
100 m < h < 6000 m a.g.l.	C_n^2 microwave; Model for ground-based clear-air FM-CW Doppler radars; Determines velocity variance, t.k.e. dissipation rate, and wind shear.	Gossard et al. (1982) NOAA Wave Propagation Laboratory, Boulder, CO
0.01 km < h < 20 km a.g.l.	C_n^2 optical, infrared, and microwave; -2/3, -4/3 power law profile expressions; Additional empirical models based on tropospheric wind observations.	Good et al. (1988) Air Force Geophysical Laboratory, Hanscom AFB, MA
10 m < h < 4200 m a.g.l.	C_n^2 microwave; Radiosonde temperature, humidity, and wind speed model; Includes formulations of Tatarski (1971); Includes algorithm to calculate turbulence due to intermittency.	d Auria et al. (1993) University of Rome, Italy
5 km < h < 25 km a.g.l.	C_n^2 optical; Radiosonde temperature, humidity, and wind speed model; Includes formulations of Tatarski (1971); Includes length scale information based on regression analyses of tropospheric and stratospheric winds.	Dewan et al. (1993) Air Force Geophysical Laboratory, Hanscom AFB, MA
0.1 km < h < 20 km a.g.l.	C_n^2 optical; Single balloon-borne temperature sensor model; Includes higher-order structure function vertical differencing algorithm.	Walters (1995) Naval Postgraduate School, Monterey, CA

Table 3. List of selected computer models used to determine optical turbulence (refractivity) and C_n^2 profile information.

Range	Model summary	Lead Scientists / Laboratory, Agency, or University
10 m < h < 1200 m a.g.l.	C_n^2 microwave; 4D refractivity field forecast model; Temperature, wind speed, and humidity gradients derived from Navy hydrostatic mesoscale numerical model.	Burk and Thompson (1997) Naval Research Laboratory, Monterey, CA
10 m < h < 2000 m a.g.l.	C_n^2 microwave; 3D time-dependent fields of turbulent refractivity calculated using a large eddy simulation (LES) model for the daytime boundary layer, convective case.	Gilbert et al. (1999) National Center for Physical Acoustics Univ. of Mississippi, MS
0.1 km < h < 25 km a.g.l.	C_n^2 optical; Operational forecast model; Includes the Dewan (1993) turbulence profile model; Temperature, humidity, and wind speed gradients (300-1000 m vertical grid) derived from the NCAR-Penn State MM5 mesoscale numerical model	Ruggiero and DeBenedictis (2000) Air Force Research Laboratory Hanscom, AFB, MA
10 m < h < 1200 m a.g.l.	C_n^2 microwave; 4D refractivity field forecast model; Temperature, wind speed, and humidity gradients derived from the UK Meteorological Office, non-hydrostatic, mesoscale numerical model	Atkinson et al. (2001) University of London, UK

4. Discussion

The previous section presented a review of selected optical turbulence research in diverse microclimate environments. Optical sensor type, wavelength, and model information were given to describe methods for determining values of C_n^2. A critical analysis of the database reveals that measured and modeled estimates of C_n^2 have mainly been reported for horizontally homogeneous sites. Table 1 confirms that the bulk of existing line-of-site optical sensor data were collected over relatively flat grass-covered fields, farmlands, desert mesas, or coastal seas. Table 2 shows that the bulk of existing atmospheric computer models for estimating C_n^2 are primarily those that incorporate traditional turbulence theory, which presumes steady state and horizontally homogeneous conditions. Table 3, in contrast, lists C_n^2 data derived either from atmospheric soundings or numerical forecast models of the wind speed, humidity, and temperature fields. These data better represent optical turbulence information brought about by larger scale motions and fluctuations of the atmosphere than those of the type closer to the ground. Turbulence in the atmospheric surface and boundary layers are more likely to be brought about by variations in terrain, the landscape, surface roughness, vegetation, and soil moisture.

However, there are known difficulties in the application of traditional Monin-Obukhov (1954) theory for calculating turbulence profile structure from temperature, humidity, and wind speed difference data, especially for the stable case and as ΔT temperature differences become small.

Mahrt (1998) indicated that similarity models may fail to capture turbulence effects brought about by unsteady and inhomogeneous processes that extend beyond the local domain, such as surface heterogeneity, the formation at night of low-level jets, gravity waves, or other propagated instabilities, which may at times be linked to particular mesoscale events or synoptic situations. Similarly, Frederickson et al. (2000) argued that inherent to the similarity approach (in the calculation of C_n^2) were potential sources for error due to inadequate treatment of non-stationary and non-horizontally homogeneous (non-equilibrium) conditions, such as those brought about by variable sea states and wave fields. It is clear, therefore, that improved physics-based theory and models to determine incremental atmospheric turbulence along optical lines-of-site are needed to account for temporal and spatial inhomogeneities (in C_n^2) brought about by changes in surface roughness, heat and moisture flux, and divergent wind flow.

It follows that optical turbulence (C_n^2) information will be additionally complicated to retrieve, analyze, and interpret within and around the urban landscape. Turbulence properties in cities, as described in detail by Roth (2000), might be those brought about by increased aerodynamic roughness of the urban surface (i.e., buildings, trees, large structures, etc.), irregular wind flow and diffusion patterns, high wind shears across the top of buildings, and non-equilibrium flows due to undetermined or highly variable fetch. Also, surface fluxes in urban areas, as detailed by Roth (2000), might be those brought about by intermittent sources and sinks of heat, moisture and momentum, e.g., warm or cold, wet or dry, rough or smooth, and sun lit or shaded areas which might not be necessarily co-located.

What steps, therefore, can be taken to increase the accuracy and realism of future optical turbulence and C_n^2 calculations? Initially it would be useful to extend existing models to inclined paths and sloping terrain (e.g., Venet, 1998; and Hahn et al., 1999). Then, new algorithms could be developed for calculating C_n^2 in similar environments, but containing more complex energy budgets. Ultimately, calculating small increment variations in C_n^2 over varying terrain and meteorology could be obtained from finer-scale turbulence (Navier-Stokes) computer models (Albertson and Parlange, 1999; Gilbert et al., 1999). At the same time, new experimental data can be retrieved (possibly) to advance the theory or models of this type.

5. Summary and Conclusions

Optical turbulence is important because it can significantly degrade the performance of electro-optical and infrared sensors, such as laser communications and infrared imaging systems. For example, changes in the refractive index of air along the transmission path of an optical system in free space can influence the temporal intensities of traveling light waves causing a blurring. Changes in the refractive index or air can also cause light waves to wander or change direction from their original path. Although this paper has described mainly data and models associated

with optical sensors aligned horizontally over various paths close to the ground, the paper also addresses data and models for C_n^2 through the boundary layer and troposphere. The reason for this is due to the well-known fact that that integrated optical turbulence effects (e.g., angle-of-arrival fluctuations) across ascending lines-of-site are more severe than those for descending lines-of-site. The more intense turbulence conditions are closer to an imaging sensor, the more likely it is that refraction effects will blur the viewing of distant objects. As an example, in a recent study by Hughes et al (2000), it was suggested that atmospheric (boundary layer) refraction effects of this kind might, in an extreme case, cause 10 arc-seconds of beam wander (over a distance of 300 km), which would affect deviations (at a receiver in space) of approximately 14.5 m. Such turbulence-induced refractivity, reported routinely from mountaintop observatories, has been referred to as *atmospheric or optical seeing* (Bougeault et al., 1995; Coulman et al., 1995; Walters and Bradford, 1997). This condition was studied intently during an experiment that established the first known optical communication link using lasers to a low earth orbiting satellite (Wilson et al, 1997), and has been a catalyst for new work in adaptive optics.

In summary, this report presented an analysis and review of selected optical turbulence research in diverse microclimates in an effort to identify deficiencies in the optical turbulence information database and to recommend improvements. The database consisted of selected C_n^2 data retrieved from optical sensors and selected C_n^2 data derived using atmospheric computer models. Critical analysis of the database showed that,

- The bulk of existing line-of-site optical sensor data were collected over relatively flat and horizontally homogeneous areas.
- The bulk of existing atmospheric surface layer computer models for estimating values of C_n^2 incorporate traditional Monin-Obukhov (1954) turbulence theory.
- The bulk of existing refractivity – C_n^2 profile calculations had been developed for use over coastal and ocean regions.
- Optical turbulence data and models have not yet been provided for inhomogeneous turbulence conditions, e.g., those that occur in urban environments or environments with changing topography and energy budgets.
- Realistic and accurate optical turbulence theory and models do not exist for all microclimate environments.
- Calculating small increment variations in C_n^2 over varying terrain and meteorology can be obtained using finer-scale turbulence (Navier-Stokes) computer models.
- New experimental data can be retrieved in more complex areas (possibly) to advance optical turbulence theory and future models.

Improved physics-based theory and models will increase the accuracy and realism of future optical turbulence and C_n^2 calculations and provide enhanced information on the performance of electro-optical sensors. This will especially benefit users of free-space optical and ground-to-satellite laser communications systems.

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13. ABSTRACT (Maximum 200 words)

Due to the increased use of laser and ground-to-satellite communications the need for reliable optical turbulence information is growing. Optical turbulence information is important because it describes an atmospheric effect that can degrade the performance of electromagnetic systems and sensors, e.g., free-space optical communications and infrared imaging. However, critical analysis of selected past research indicates that there are some areas (i.e., data and models) in which optical turbulence information is lacking. For example, line-of-sight, optical turbulence data coupled with atmospheric models in hilly terrain, coastal areas, and within built-up urban areas are few in number or non-existent. In addition, the bulk of existing atmospheric computer models that are being used to provide estimates of optical turbulence are basically one-dimensional in nature and assume uniform turbulence conditions over large areas. Therefore, current optical turbulence theory and models may be critically deficient and in error for inhomogeneous turbulence conditions, such as those that occur in urban environments or environments with changing topography and energy budgets.

This paper summarizes selected past research on optical turbulence and the refractive index structure parameter (C_n^2) in diverse microclimates in an effort to identify deficiencies in the optical turbulence information database and to recommend improvements. The database presented here contains optical turbulence (C_n^2) information at different wavelengths and for different microclimate environments, e.g., in rural, hilly, desert, mountain-valley, urban, coastal, ocean, and arctic. The database includes several examples of measured and modeled values of C_n^2 in the atmospheric surface and boundary layers.

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Atmospheric turbulence, refractive index structure parameter, scintillometer, database, computer models, surface layer, boundary layer, electro-optical, infrared, microwave, laser, imaging, communications, advanced soldier systems

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